THE EFFECTS OF TEMPERATURE AND HUMIDITY ON FATIGUE.

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The physiologist in his fondness for investigating internal mechanisms is prone to overlook the important fact that the living body exists in the midst of a multitude of external conditions. These conditions furnish stimuli to the living tissues, augmenting or diminishing their actions, and such stimuli play an important part in determining the activities and correlations of the internal mechanisms. The organism as a whole in the midst of its environmental conditions must establish for itself at each successive moment a balance in the work of its various parts. If one of the conditions is altered this balance is by so much disturbed. Within limits, and even within wide limits for brief periods, such a disturbance is borne with impunity: a readjustment to the altered situation occurs; a new balance is struck; and no harm results. But if the limits be much or long surpassed the normal adaptation gives place to a pathological state which is detrimental to the organism.

Of the two environmental conditions here in question, the temperature and the humidity of the air, there exists a certain medium range of variation within which the human body is capable of performing its best work. Even when adapted to this optimum it may be subjected for a considerable period of time to a high temperature or a low temperature, to a high humidity or a low humidity, without serious disturbance of its organic balance. One need not be a man of science to realize this truth; one needs not to live outside of our own America, famed for its fitful climate. But prolonged exposure to extremes of these conditions does not conduce to the continuance of a normal physiological state. The effects of a low temperature and a low humidity have not been studied as fully as have those of the opposite extremes, and these two latter have especial significance when they are associated with one another. I propose therefore to confine myself to a discussion of the physiological and pathological relations of the living body when subjected simultaneously to high temperature and high humidity.

We may observe these relations on many of the hot and humid summer days in our American cities. We may observe them when one who is adapted to a temperate climate goes to live in the tropics. They are well illustrated in various industrial occupations, such as mining, baking, laundering, and some varieties of cotton weaving. The effects of exposure to the atmosphere of these situations are many and various. The bodily mechanism for resisting external heat is at once brought into action. The blood vessels of the skin become dilated and charged with blood, the skin becomes heated, and the sweat glands become active. From the skin there occurs a loss of bodily heat by radiation, conduction, convection and the evaporation of perspiration. The loss of heat by these processes, amounting, according to Rubner,* to 95.25 per cent. of the total heat loss, may suffice for a time to keep the bodily temperature at its normal level. In proportion, however, as the temperature of the air approaches or surpasses that of the body and the humidity of the air is sufficient to prevent the evaporation of sweat, loss of bodily heat by the customary channels becomes lessened. Without adequate means for eliminating the heat that is being constantly produced within, the internal temperature rises and a febrile condition results. Such a state is reached the sooner, the more mechanical work is performed and the more heat is thereby produced. Its oncoming is favored also by a lack of movement in the air. With a continuance of the unfavorable environmental conditions a simple rise of internal temperature may pass into a higher fever characteristic of simple heat prostration, or a moderately severe heat stroke with a temperature up to 40.6°C. (105°F.), and finally into the hyperpyrexial or intense form of heat stroke, in which the bodily temperature has been known to rise to the phenomenal height of 47.6°C. (117.8° F.). That the elevation of bodily temperature is the result of an elevation of external temperature and humidity combined has been well shown by various British authorities† whose information is drawn partly from laboratory experiments and partly from observations in mines and factories. Haldane‡ summarizes the results of his observations as follows:

"These experiments proved that in very warm air it is the temperature indicated by the wet-bulb thermometer (not the actual air temperature as shown by the dry-bulb thermometer, nor the amount of moisture in the air, nor the relative humidity) which determines the ill-effects produced. With a wet-bulb temperature exceeding 88° to 90° [F. = 31° to 32°C.] in fairly still air the body temperature begins to rise, even in the case of persons stripped to the waist and doing no work; and when once started this rise continues until symptoms of heat stroke arise, unless the person leaves the warm air. In the case of persons doing muscular work, the rise of body temperature is much more rapid and begins at a much lower wet-bulb temperature. It will, for instance, begin (in persons stripped to the

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* Rubner; Lehrbuch der Hygiene, 8th Edition, 1907, p. 90.

† Reports of the Departmental Committee on Humidity and Ventilation in Cotton Weaving Sheds, London, 1909 and 1911.

‡ Haldane: Report of the Departmental Committee, etc., Appendix III, p. 218.

waist) at a wet-bulb temperature of about 80° [F. =26.7°C.] in still air with moderately hard muscular work, so that hard and continuous work is impracticable at wet-bulb temperatures of over 80° in still air. There is no doubt that when ordinary clothes are worn, serious rise of body temperature occurs at a still lower wet-bulb temperature. Soldiers marching in uniform are, for instance, liable to heat stroke at wet-bulb temperatures of under 70° [F. =21°C.]."

A second striking effect of a combined high temperature and high humidity is a disinclination or actual inability to perform active muscular work. Beginning as a mere inertness, accompanied by sleepiness, which may readily be resisted for a time, it may pass into a genuine condition of fatigue, and ultimately into the exhaustion of heat stroke. Haldane* says of the Cornish miners of tin and copper: "They do not . . . seem to be able to do more than a limited amount of work. The leisureliness of all work in the mine is in very striking contrast to what may be observed in any ordinary English colliery of about the same depth." Pembrey,† after studying the effects of warm moist temperatures upon himself, medical students and soldiers, concludes: "The results show definitely that a man is much less efficient in a warm moist atmosphere. . . . A man can do far more work with less fatigue at a low wet-bulb temperature than at a high one." Pembrey and Collis,‡ in speaking of the physiological effects of the warm, moist atmosphere of cotton weaving, say: "The natural tendency is for the nervous system to become less active and for muscular work to be diminished. In a weaving shed, however, the machine sets the pace and the worker must neglect the dictates of his sensations, which are the natural guardians of his health and well-being. . . . It is not surprising, therefore, that at the end of a day's work many of the weavers complain that they have no energy left, have no great desire for food, and need only drink and rest." Boycott§ says of mining in hot moist air: "My observations on miners . . . lead me to conclude that their power of doing work under these circumstances is quite small." Cadman,¶ professor of mining in Birmingham University and late H. M. Inspector of Mines, gives more detailed observations to the effect that from about 25° C. (77° F.) wet-bulb reading, exertion begins to be accompanied by depression, and disinclination to work increases rapidly with an increasing wet-bulb temperature. At 27.8°C. (82°F.) "if clothes be removed and maximum body surface exposed work can be done providing current of air is available." At 29.4°C. (85°F.) "only light work is possible"; and at 35°C.

* Haldane: Journal of Hygiene, 1905, V, p. 498.
† Pembrey: Report of the Departmental Committee, etc., 1909, Appendix IV, p. 221.
‡ Pembrey and Collis: Second Report of the Departmental Committee, etc., 1911, Appendix III, p. 24.
§ Boycott: Report of the Departmental Committee, etc., 1909, Appendix V, p. 222.
¶ Cadman: Report of the Departmental Committee, etc., 1909, Appendix VIII, p. 225.

(95°F.) "work becomes impossible." Stapff* observed in the construction of the St. Gotthard tunnel that the laborers, working in an atmosphere often completely saturated with moisture and with a temperature rising at times beyond 30°C. (86°F.) as measured by the dry-bulb thermometer, experience not only great discomfort, but indifference, enervation, weariness and exhaustion. These direct statements are supplemented by the testimony of many industrial workers and observers of industrial conditions to the effect that combined high temperature and high humidity cause not only bodily discomfort but lessened power of labor. All who have experienced such conditions cannot fail to agree with such testimony.

But the lessened power of labor under such circumstances may be real or only apparent. The sensations of fatigue which are undoubtedly present may diminish the amount of labor performed; but sensations of fatigue are often misleading and do not necessarily signify the presence of the actual physical basis of fatigue. Unfortunately there seems to have been made no exact comparative studies of the actual amount of labor which the human body is capable of performing under these abnormal conditions. This is but one instance of a lamentable lack of exact information regarding the capabilities of the body under different environmental conditions. This lack can be supplied only when we have devised adequate methods of testing the working powers of the living individual. Patrizi† has indeed shown that human muscles when subjected to localized hot baths, as by the immersion of the arms in hot water, and then stimulated electrically, undergo early fatigue and rapid exhaustion. This result is in harmony with those of Gad and Heymans‡ and others, who find that the excised muscles of frogs become rapidly fatigued when warmed. From all the available evidence therefore it seems probable that the actual physical basis of fatigue is present in a body working in a hot and humid atmosphere. A more detailed analysis of the physical and chemical conditions of such a body confirms this conclusion and, I venture to think, throws considerable light upon this hitherto obscure subject.

When in a hot and humid atmosphere the blood vessels of the skin are dilated and overcharged with blood, the brain and spinal cord among other organs are rendered correspondingly anemic. This is sufficient of itself to account largely for the feeling of weariness, the indifference and apathy toward laboring that are then present. The changed bodily sensations and the general bodily discomfort may also tend toward the same end.§ But if the stage of elevated bodily temperature be reached, the internal conditions are still more radically changed. A febrile state, especially

* Stapff: Archiv für (Anatomie und) Physiologie, 1879, Supplement Band, p. 91.
† Patrizi: Archives italiennes de biologie, 1893, XIX, p. 105.
‡ Gad und Heymans: Archiv für (Anatomie und) Physiologie, 1890, Supplement Band, p. 59.
§ Hough: American Journal of Public Hygiene, 1910, XX, p. 267.

when pronounced and long continued, affords unusually good chemical conditions for the oncoming of fatigue. One of the striking metabolic accompaniments of the fevers that result from bacterial invasion of the living body is an increased excretion of nitrogen, which is derived, as is inferred from the work of various investigators, from an increased destruction of the proteins of the tissues, probably due largely to the direct action of the higher temperature upon them. This abnormal destruction of proteins appears to occur not only in fevers of bacterial origin but in the hyperthermy produced by hot baths and in other ways. Schleich,* Formanek,† Edsall‡ and others, have found this to be the case. It was long ago maintained that along with the increased destruction of proteins in fevers there is an incomplete oxidation of intermediate metabolic products. In this connection, it is interesting to recall that Mandel§ finds purin bases to be increased and uric acid to be decreased in quantity in febrile urine. Furthermore, Geppert,¶ Minkowski|| and Kraus** argue from the diminished quantities of carbon dioxide in the blood and from other facts that there occurs an acid intoxication during fevers. Ammonia, indicating also the production of acids, is increased in output.†† Acetone and even diacetic and oxybutyric acids have frequently been found in febrile urine.‡‡ While it is still in doubt whether these acetone bodies arise from destroyed proteins or from destroyed fats, the fact of their existence as intermediate metabolic products seems clear.

Whether analogous changes occur in the hyperthermy resulting from exposure to a hot and humid atmosphere has not yet been sufficiently investigated, but it seems altogether probable that in such cases there is at least a great disturbance of metabolism. The theory of auto-intoxication as the essential causative factor in insolation was first suggested by Vincent in 1888.§§ It was adopted by Van Gieson,¶¶ Levene,|||| and Lambert*** in their investigations of sunstroke during the extraordinary occurrence of that disease in the city of New York in the summer of 1896. The symptoms of the disease suggest strongly the presence within the body of an acute poison. Levene found that the blood serum of two patients suffering from

* Schleich: Archiv für experimentelle Pathologie und Pharmacologie, 1875, IV, p. 82.
† Formanek: Sitzungsber. d. Kais. Akad. d. Wiss. Math. nat. Cl., Wien, 1892, 101, p. 278.
‡ Edsall: Transactions of the Association of American Physicians, 1909, XXIV, p. 625.
§ Mandel: American Journal of Physiology, 1904, X, p. 452; 1907, XX, p. 439.
¶ Geppert: Zeitschrift für klinische Medizin, 1881, II, p. 355.
|| Minkowski: Archiv für experimentelle Pathologie und Pharmacologie, 1885, XIX, p. 209.
** Kraus: Zeitschrift für Heilkunde, 1889, X, p. 106.
†† Erben: Zeitschrift für Heilkunde, 1904, V, p. 33.
‡‡ MacCallum: Archives of Internal Medicine, 1909, II, p. 594. Also Harvey Lectures, 1908–9, p. 27.
§§ Vincent: L'hyperthermie. Thèse de Bordeaux, 1887–88. Number 8.
¶¶ Van Gieson: New York State Hospitals Bulletin, 1896, I, p. 475; Medical Record, 1900, LVII, p. 1134.
|||| Levene: New York State Hospitals Bulletin, 1897, II, p. 357.
*** Lambert: Loomis and Thompson's "A System of Practical Medicine," 1898, article on "Insolation"; Medical News, 1897, LXXI, p. 97.

the disease, as well as the urine of convalescent patients, was acutely toxic to rabbits; and although he was unable to demonstrate any increased nitrogenous metabolism he came to the conclusion that the symptoms of sunstroke result from an auto-intoxication due to some kind of a pathological decomposition of tissue. Van Gieson described histological changes in the nerve cells of the brain and spinal cord which are closely similar to those produced by various poisons, such as other auto-intoxicants, bacterial toxines, alcohol and lead. Analogous lesions have been observed in either insolation or artificial heating by Goldscheider and Flatau,* Marinesco,† and Amato.‡ Various investigators § have found that when the temperature of the body has been raised, either experimentally or in insolation, the alkalinity and coagulability of the blood may be diminished. Another fact of significance is the unusually early appearance of rigor mortis and decomposition after death from insolation,¶ which suggests that an acidity may have developed in the muscles. From these various observational and experimental data it may be inferred, if not with certainty at least with a high degree of probability, that the subjection of a body to an external temperature and humidity sufficient to raise the internal temperature to a pathological degree causes metabolic changes, the nature of which is not yet known but which interfere profoundly with the normal working of internal mechanisms.

Fatigue is a physical phenomenon, a lessened power of work, which has as its basis certain metabolic phenomena. The two chemical causes of fatigue have long been recognized as the diminution of substance that is essential to activity and the accumulation of metabolic products that are toxic or depressing to the tissues. Of these fatigue substances carbon dioxide and lactic acid appear to play a prominent rôle in the production of normal fatigue.|| It is probable, as I have elsewhere maintained,** that these are but types of other metabolic substances which act similarly. This is seen most clearly in certain pathological conditions. It is well-known that in diabetes, for example, there exists an acid intoxication conditioned by the presence in the blood and tissues of β-oxybutyric acid and other acetone bodies. I have been able to show that when β-oxybutyric acid, either free or as a salt, is administered by irrigation to a muscle, the muscle behaves as if it had been fatigued by exhaustive labor, and I have explained

* Goldscheider und Flatau: Fortschritte der Medizin, 1897, XV, p. 245; do., 1898, XVI, p. 124. Cf. Moxter, do. p. 121, and Goldscheider und Brasch, do. p. 126.

† Marinesco: Comptes rendus de l'Academie des Sciences, Paris, 1906, CXLIII, p. 853.

‡ Amato: Virchow's Archiv, 1909, CXCV, p. 544.

§ Wood: Sunstroke, 1872, pp. 86 and 93; Thermic Fever, Pepper's System of Medicine, 1886, V, p. 392. Lambert: *Loc. cit.*

¶ Lambert: *Loc. cit.*

|| Lee: Journal of the American Medical Association, 1906, XLVI, p. 1491; also Harvey Lectures, 1905–6, p. 169; American Journal of Physiology, 1907, XX, p. 170; Popular Science Monthly, 1910, XXVI, p. 182.

** Lee: British Medical Journal, 1906, II, p. 1806.

the well-known proneness to fatigue of an individual suffering from diabetes as due in considerable part to the direct action on the tissues of β-oxybutyric acid and perhaps other associated pathological fatigue substances. It is probable that a similar explanation will hold for inanition, the pernicious vomiting of pregnancy, and the various other instances of acid intoxication, all of which are characterized by marked fatiguability. What has been said of β-oxybutyric acid is equally true of indol, which likewise is depressing to muscle and the presence of which in abnormal quantities within the body is associated with a similar tendency to fatigue.* It has been maintained † that the inability to perform continued labor that is so pronounced in neurasthenia rests likewise upon analogous metabolic causes, the identity of which has not yet been established. I think it probable that future research will greatly extend our knowledge of the metabolic bases of fatigue. Especially do I look for such a rôle to the intermediate metabolic products which may be present in abnormally large quantities in various pathological states. Such a conception too appears to me to afford the most probable explanation of the fatigue that appears to be present when the individual is endeavoring to labor in an atmosphere at a high temperature and a high humidity. Here he has to contend not only with his normal fatigue substances, but with the pathological substances that result from the peculiar conditions of his labor.

But there is a further factor to be considered. More than a hundred years ago Alexander von Humboldt ‡ observed that heat increases the action of various chemical substances on various forms of living substance, such as the heart and the motor nerves. This has since been studied in many ways by many investigators, such as Hermann, § Kronecker, ¶ Luchsinger, || Lauder Brunton and Cash, ** Richet, †† and others, and it has become recognized as a general law, that the temperature at which poisons act upon living substance is a factor, as in other chemical phenomena, in determining the degree of their action—at a higher temperature their action is more intense. There seems to be no reason why this law should not apply to the case under consideration. This suggestion has indeed been made for normal fatigue substances by Patrizi ‡‡ to explain the ready fatiguability of human muscles submitted to localized hot baths. With even greater weight

* Lee: in Herter's The Common Bacterial Infections of the Digestive Tract, 1907, p. 254.

† Cowles: Neurasthenia and Its Mental Symptoms, 1891; cf. also Ballet; Neurasthenia, translated by P. Campbell Smith, 1911, translator's preface, p. XIX.

‡ von Humboldt: Über die gereizte Muskel-und Nervenfaser, 1797, II, p. 218.

§ Hermann: Archiv für (Anatomie und) Physiologie, 1867, p. 64.

¶ Kronecker: Archiv für (Anatomie und) Physiologie, 1881, p. 357.

|| Luchsinger: Thermisch-toxicologische Untersuchungen, in Grützner und Luchsinger's Physiologische Studien, 1882, p. 33.

** Lauder Brunton and Cash: Journal of Physiology, 1882, IV, p. 1.

†† Richet: La chaleur animale, 1889, p. 213.

‡‡ Patrizi: *Loc. cit.*

it can be applied to the human being laboring under the disadvantageous conditions of excessive temperature and excessive humidity. Normal and pathological fatigue substances are here present in solution in an overheated body. If they are toxic at normal degrees of temperature, their toxicity is more pronounced at higher degrees, and in proportion as mechanical work is performed and internal temperature rises, the more is working power lessened.

I may, therefore, summarize my thoughts as follows: When an individual is subjected to an atmosphere that is charged with an excessively high temperature and high humidity, his bodily temperature is raised, his working power becomes limited, and there is an early oncoming of fatigue. In addition to the normal fatigue substances there are present other substances, products of an abnormal metabolism, perhaps of increased protein disintegration, which likewise act as fatigue substances. Both the normal and the pathological fatigue substances act toxically to diminish the activity of the tissues, and such fatiguing action is rendered greater by reason of the abnormally high internal temperature that is present.

If these considerations, presented from a purely scientific standpoint, are worthy, their significance ought to be more than merely academic. Industrialism presents numerous instances in which human beings are obliged to labor under the conditions here outlined. Constant submission to these conditions is detrimental to the well-being of the individual and ultimately of the race. This is an unnecessary situation, which sooner or later is bound to be relieved. It is the duty of men of science not merely to discover the conditions under which men labor, not merely to show how an environment is detrimental, but to use their influence to make of labor a physiological rather than a pathological exercise.